Going Deep on Spallation Backgrounds

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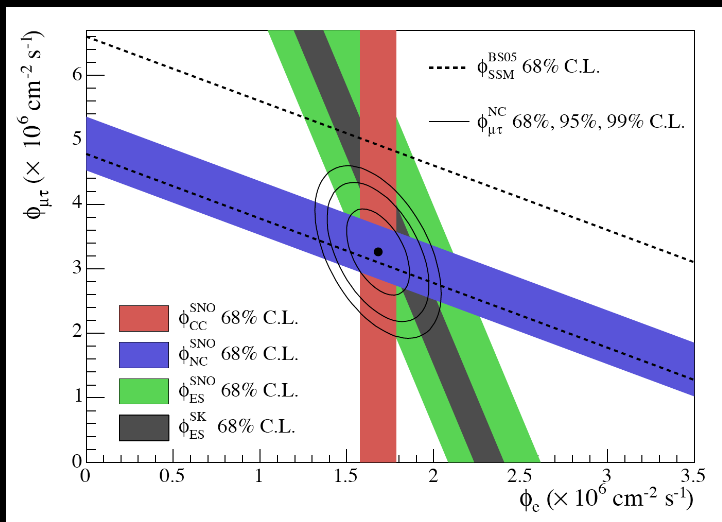
The Ohio State University's Center for Cosmology and AstroParticle Physics

CCAPP

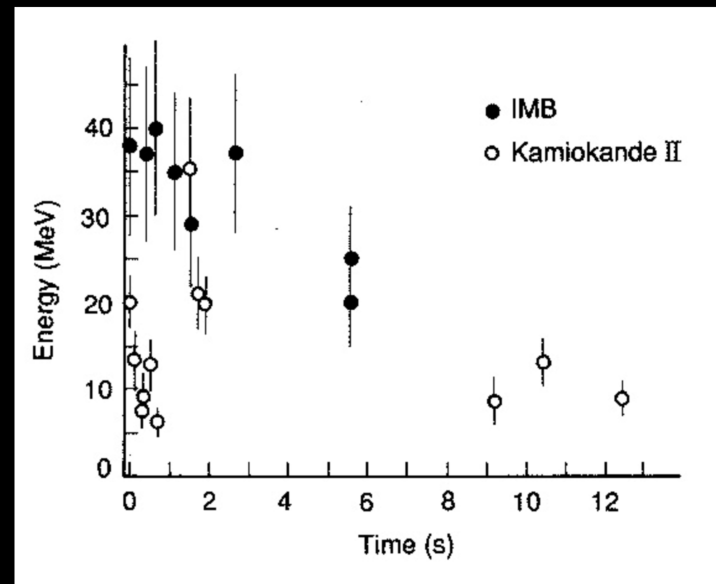
NSF

MeV Neutrinos – What are They Good For?

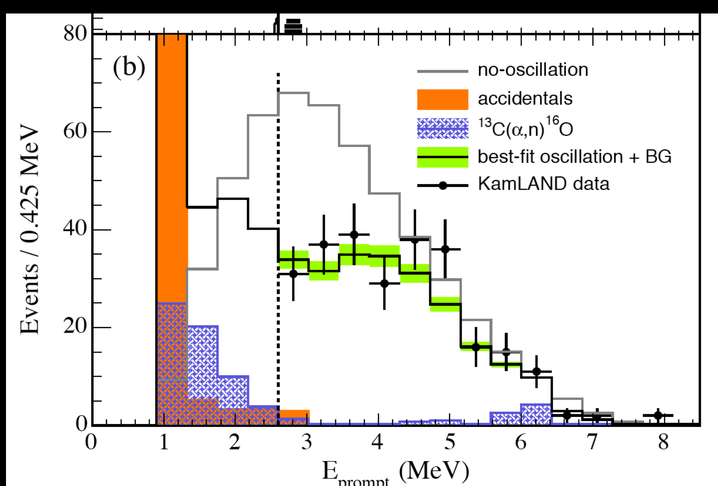
Solar



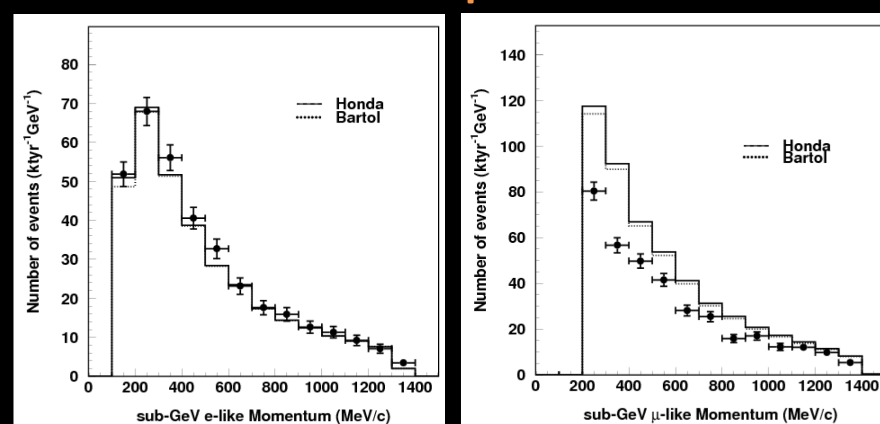
Supernova



Reactor



Atmospheric



Why is Progress Stalled?

Is it a lack of interesting questions?

No

Is it a lack of big detectors?

Sort of

Is if fixable?

Yes

Plan of the Talk

✔ Introductory exhortation

Revolutionizing MeV neutrino astronomy

Spallation: the haunting

Spallation: the summoning

Spallation: the vengeance

Back to the future with neutrino physics

Revolutionizing MeV neutrino astronomy

Basic Features of MeV Neutrino Detection

Detectors must be massive:

Effectiveness depends on volume, not area

Example signals:

$$\nu + e^- \rightarrow \nu + e^-$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

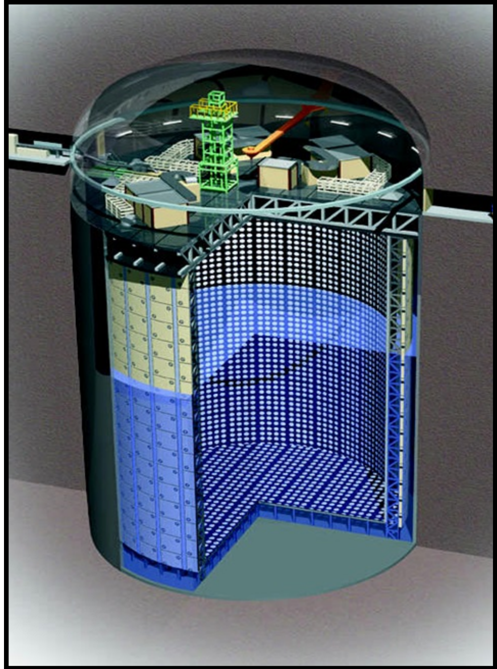
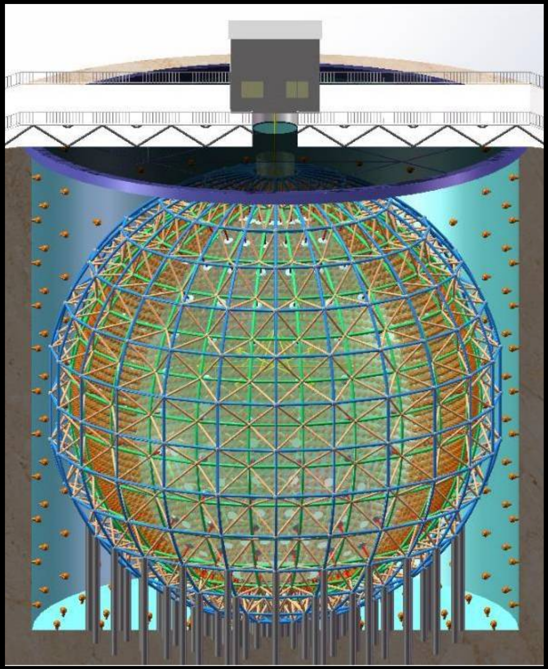
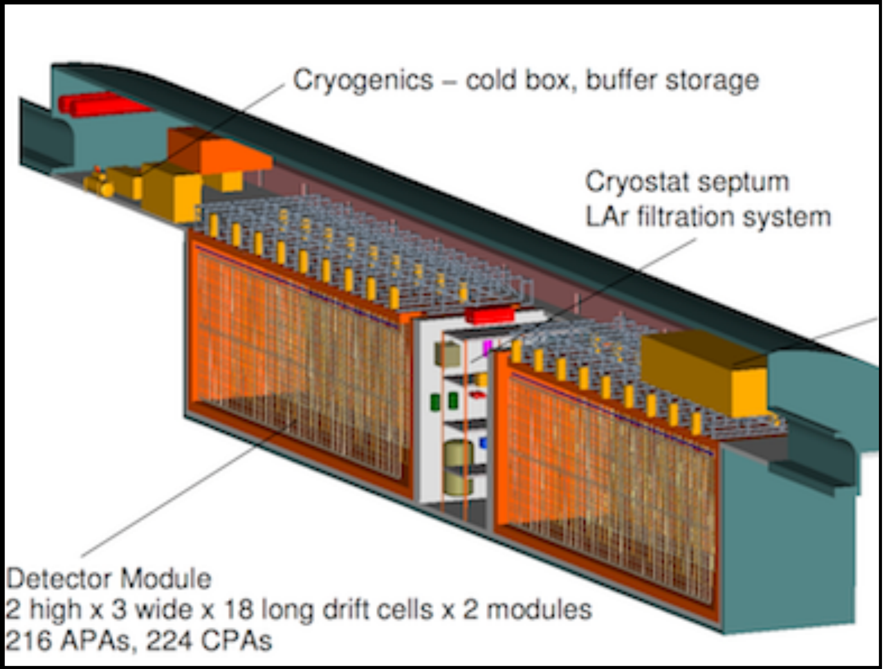
Detectors must be quiet:

Need low natural and induced radioactivities

Example backgrounds:

$$A(Z, N) \rightarrow A(Z+1, N-1) + e^- + \bar{\nu}_e$$

First: *Get Multi-kton-Scale Neutrino Detectors*

Super-K	JUNO	DUNE
		
32 kton water	20 kton oil	34 kton liquid argon
Japan	China	United States
running	*building*	*proposing*

Excellent performance or prospects for neutrino astronomy

Second: Enable Super-K Selection of Nuebar

The signal reaction produces a neutron, but most backgrounds do not

Beacom and Vagins (2004): First proposal to use dissolved gadolinium in large light water detectors showing it could be practical and effective

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

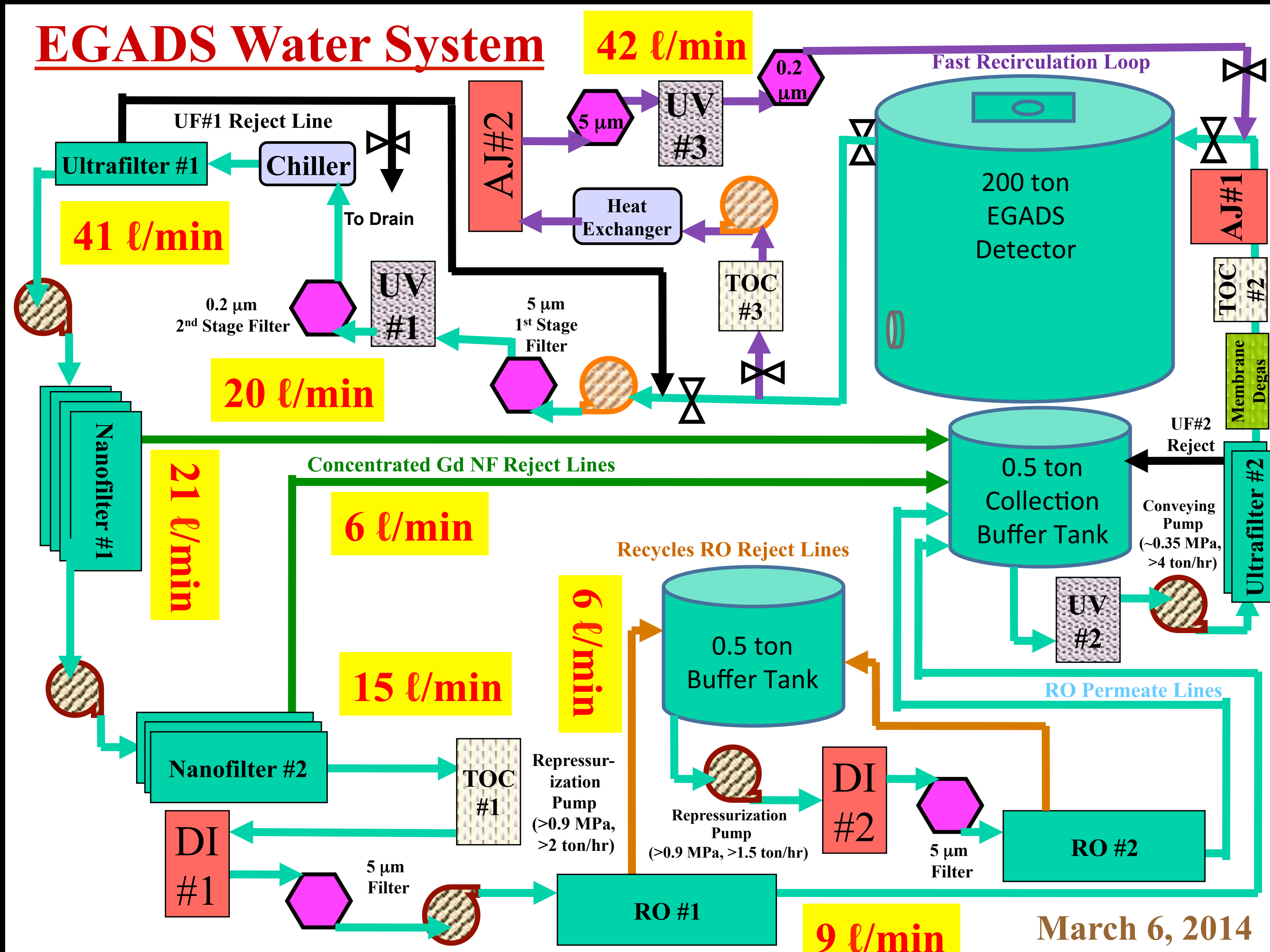
$\xrightarrow{\text{SK}}$ Neutron capture on protons
Gamma-ray energy 2.2 MeV
Hard to detect in SK

$\xrightarrow{\text{SK+Gd}}$ Neutron capture on gadolinium
Gamma-ray energy ~ 8 MeV
Easily detectable coincidence
separated by ~ 4 cm and ~ 20 μs

Mad Scientist at Work in Underground Lair

Adding 383 grams $Gd_2(SO_4)_3$ to 191 liters of H_2O; January 5th, 2011

Water and Gadolinium Filtration System



Fate of the GADZOOKS! Proposal

For about 10 years:

Vagins and colleagues developed experimental aspects

Beacom and colleagues developed theoretical aspects

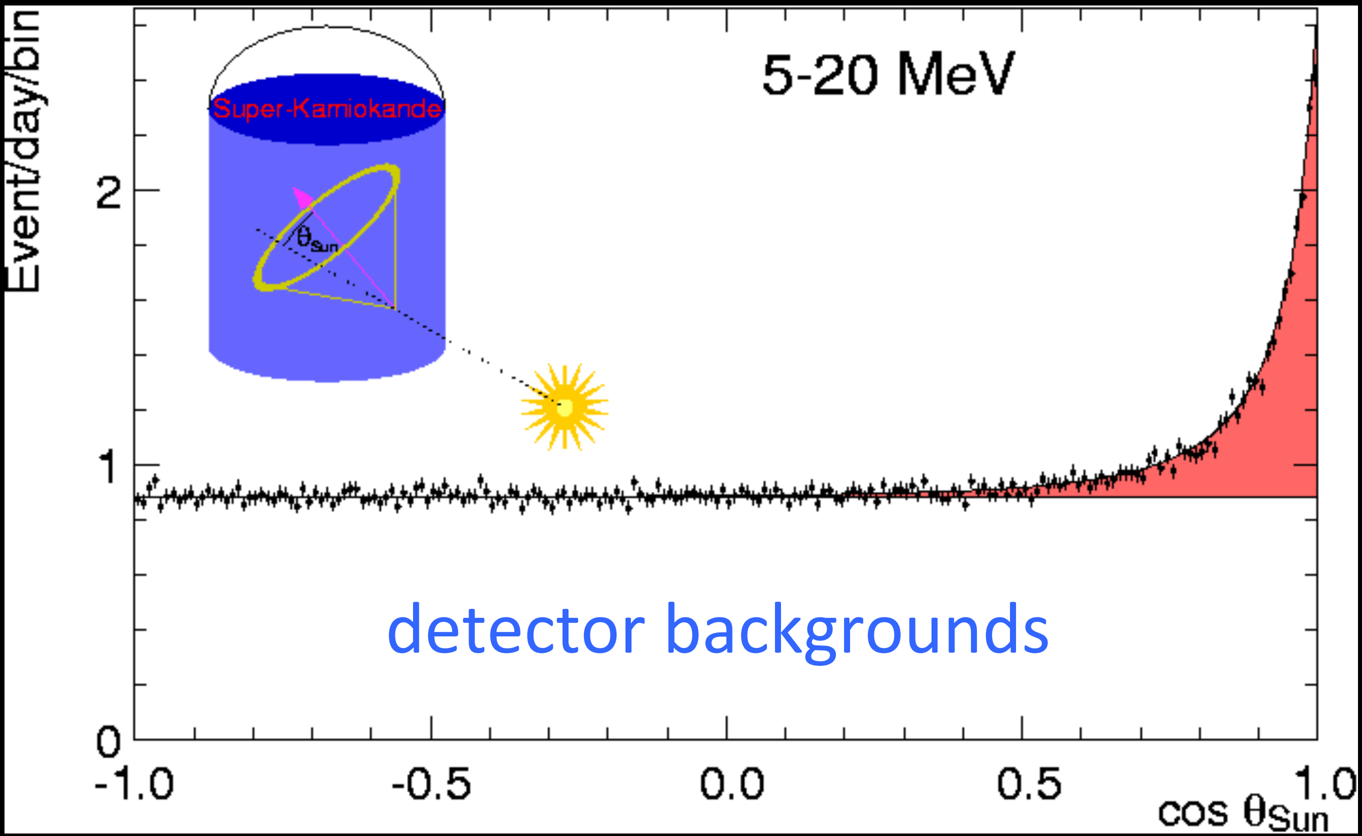
Super-K 2015: Yes

[41] Ref. [4] proposed adding a 0.2% gadolinium solution into the SK water. After exhaustive studies, on June 27, 2015, the SK Collaboration formally approved the concept, officially initiating the SuperK-Gd project, which will enhance anti-neutrino detectability (along with other physics capabilities) by dissolving 0.2% gadolinium sulfate by mass in the SK water.

Will greatly increase sensitivity for many studies

Third: Remove Detector Backgrounds

After strong cuts, still large detector backgrounds in Super-K

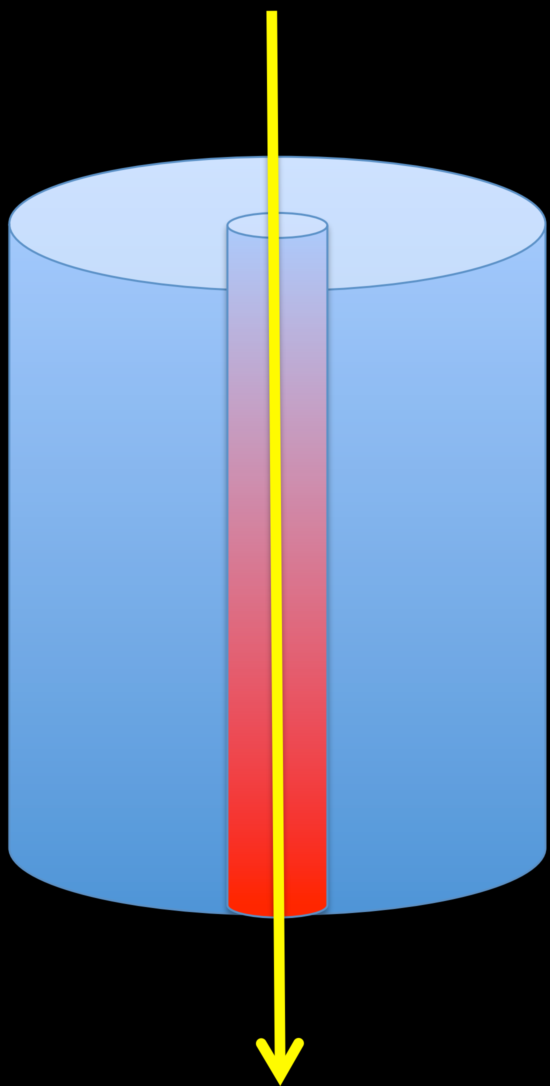


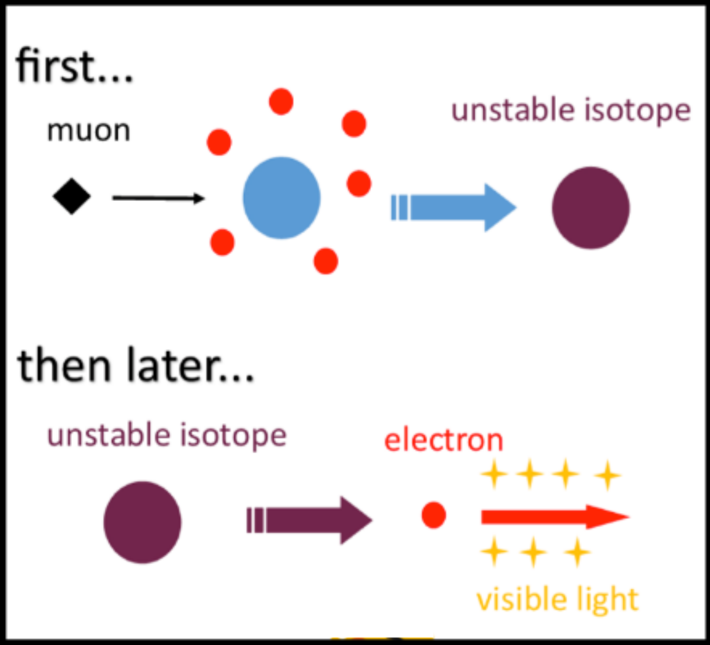
Signal is neutrino-electron scattering

Background is beta decays

What causes the backgrounds and can we remove them?

Muon-Induced Spallation Decay Backgrounds



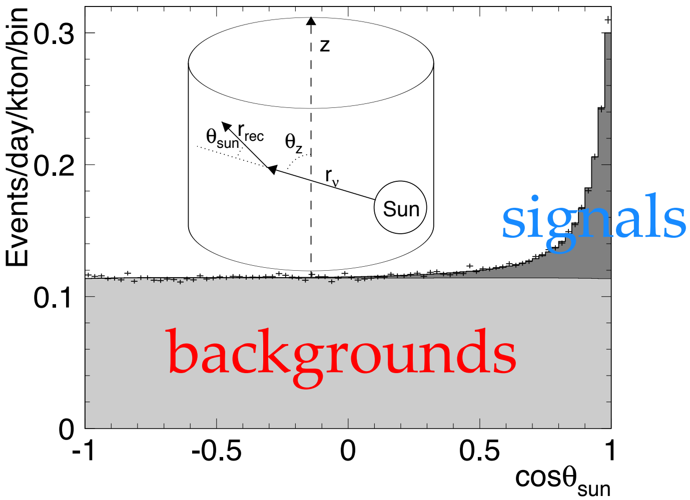


Muon passes through detector
Beta decays follow; veto in cylinder

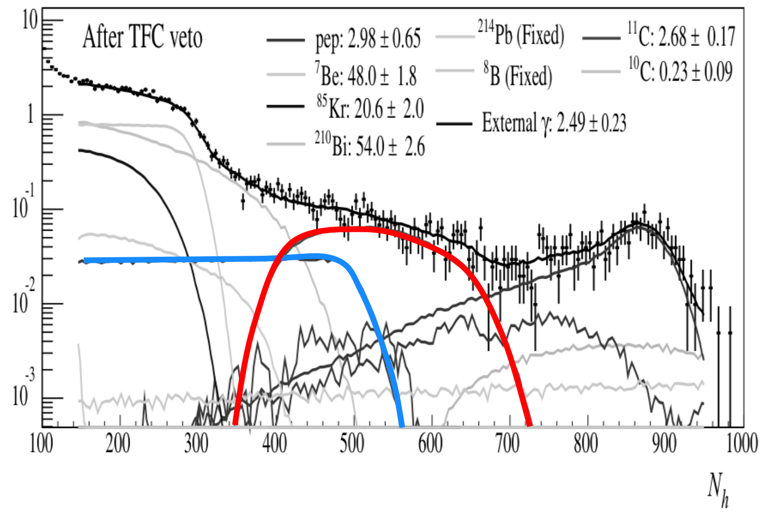
Muon rate 2 Hz; betas to ~ 30 s
Cuts face inefficiency or deadtime

Examples of Spallation Backgrounds

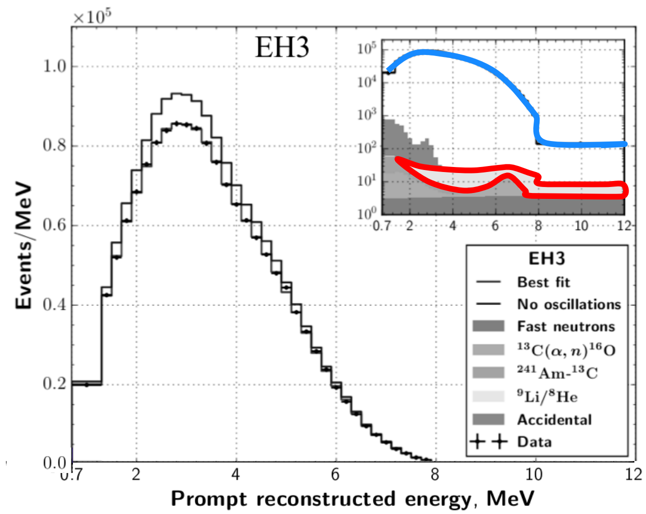
^{8}B solar neutrino



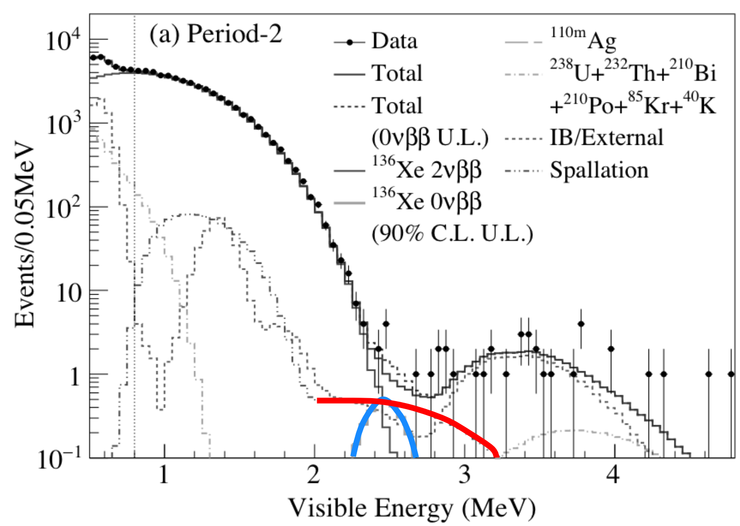
pep, CNO solar neutrino



reactor neutrino



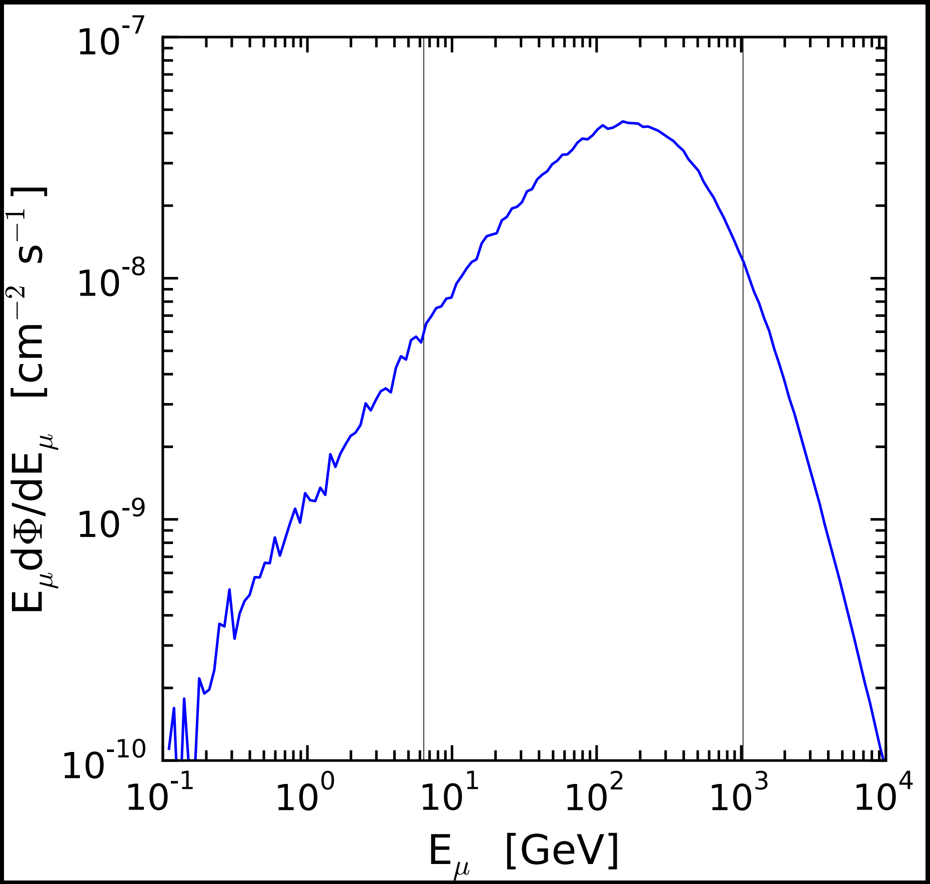
0νββ

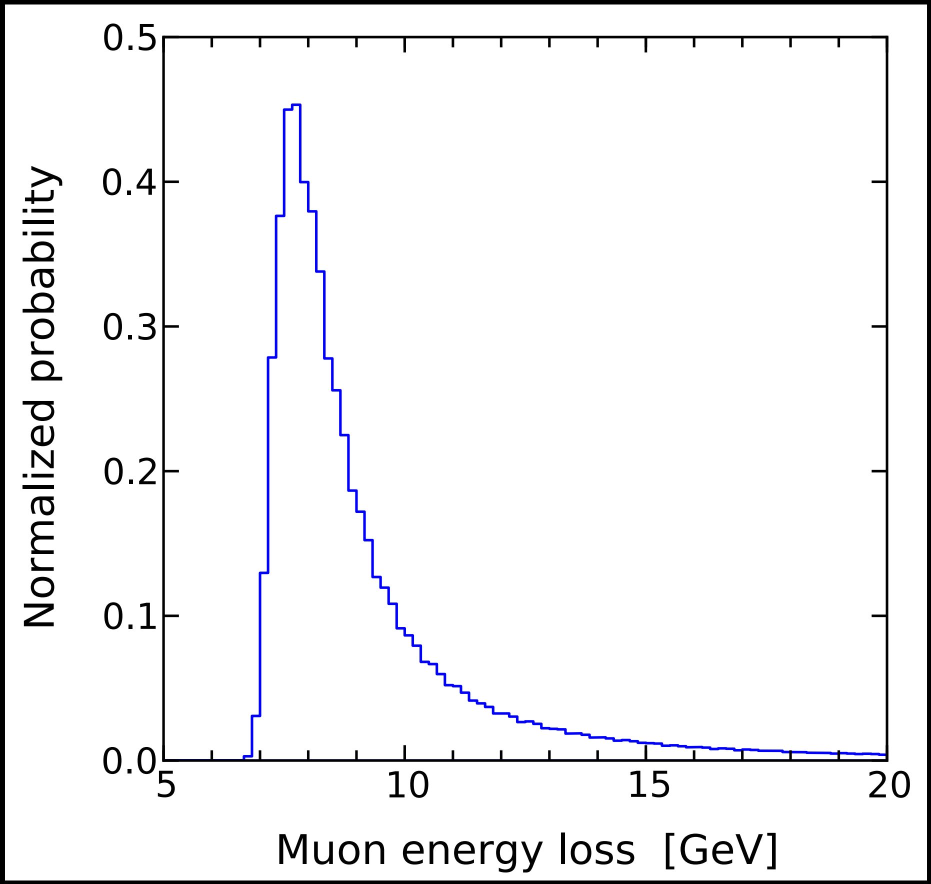


Spallation: the haunting

Li and Beacom 2014 [arXiv:1402.4687]
Isotopes are made by muon secondaries and are calculable

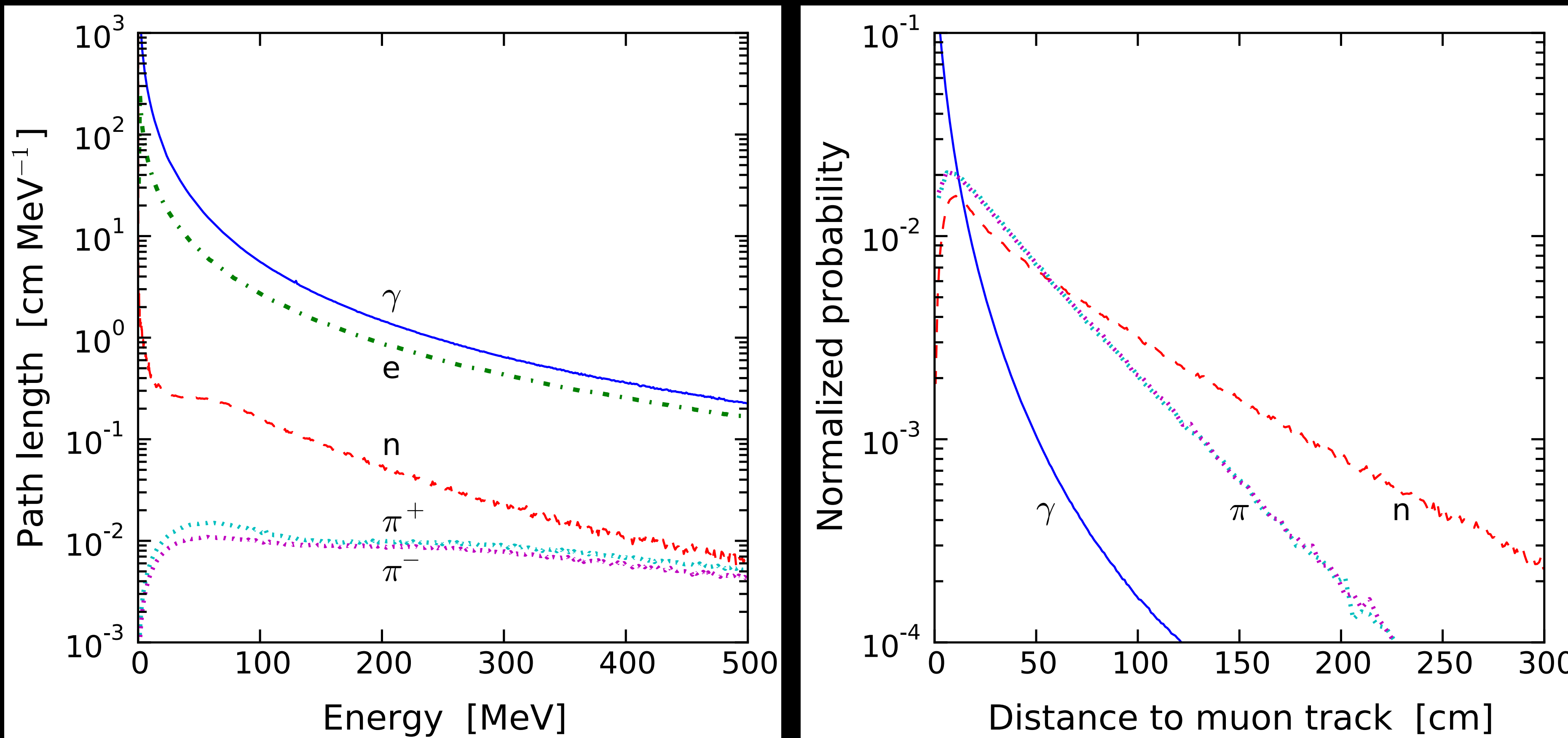
Muons and their Energy Losses





Typical muon energy is 250 GeV; typical energy loss is 8 GeV

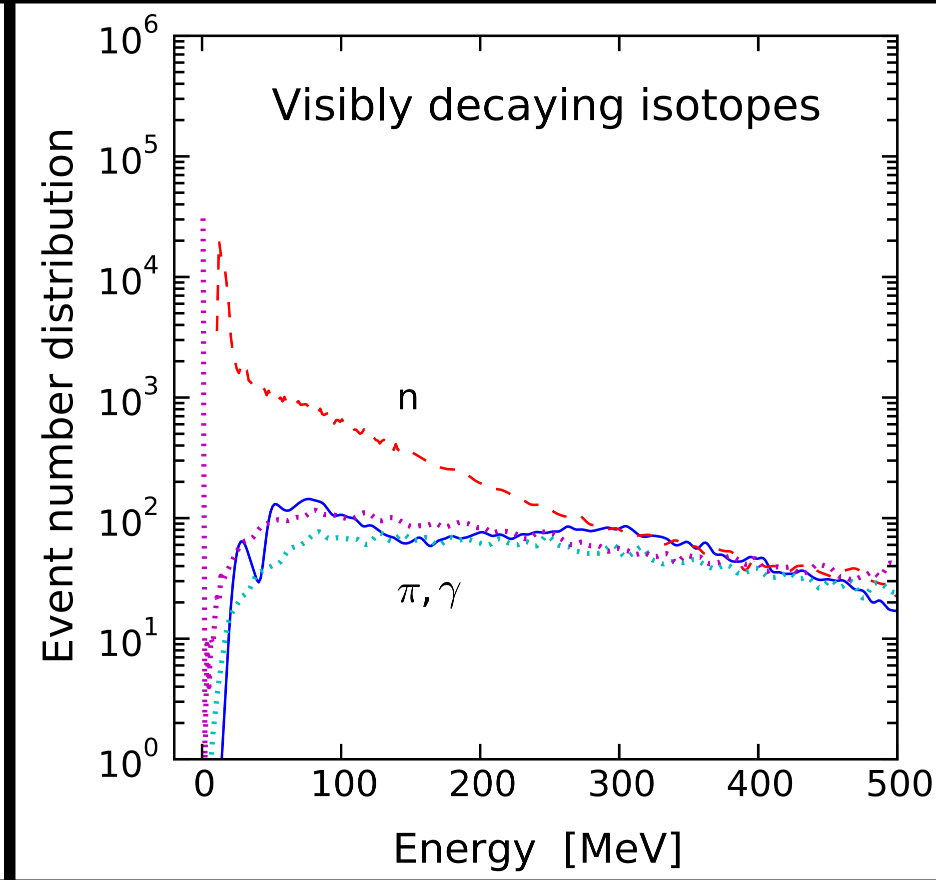
Secondary Particles and their Properties



Secondaries are abundant, low-energy, and near the track

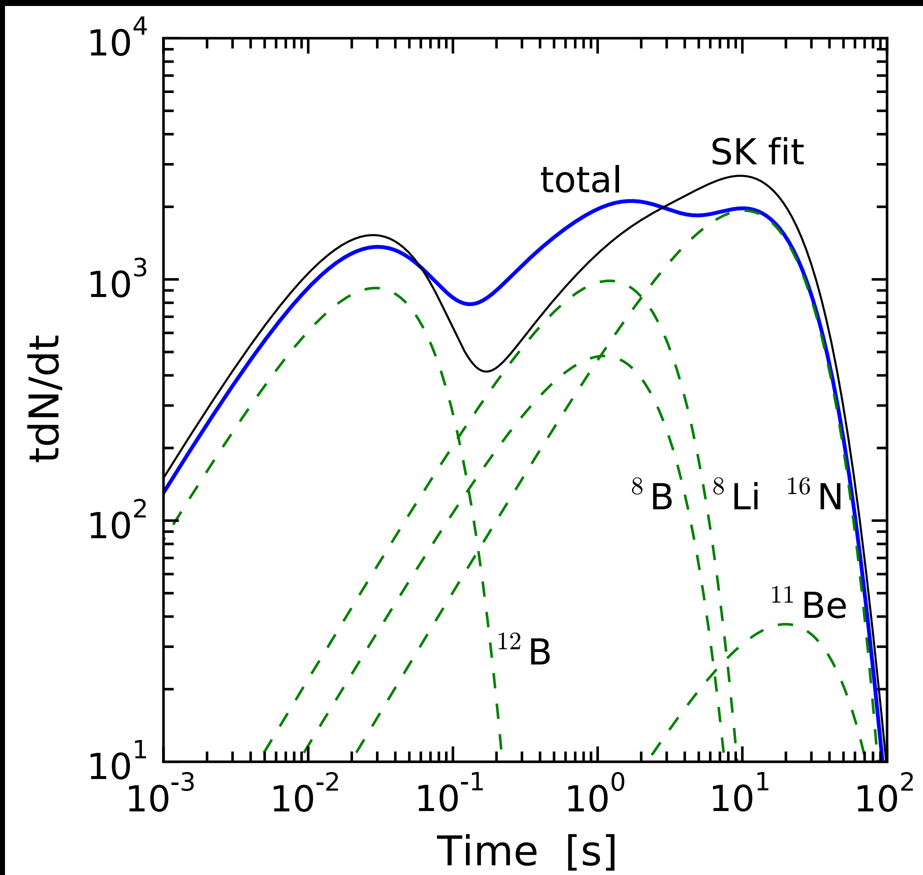
Spallation Yields and their Parents

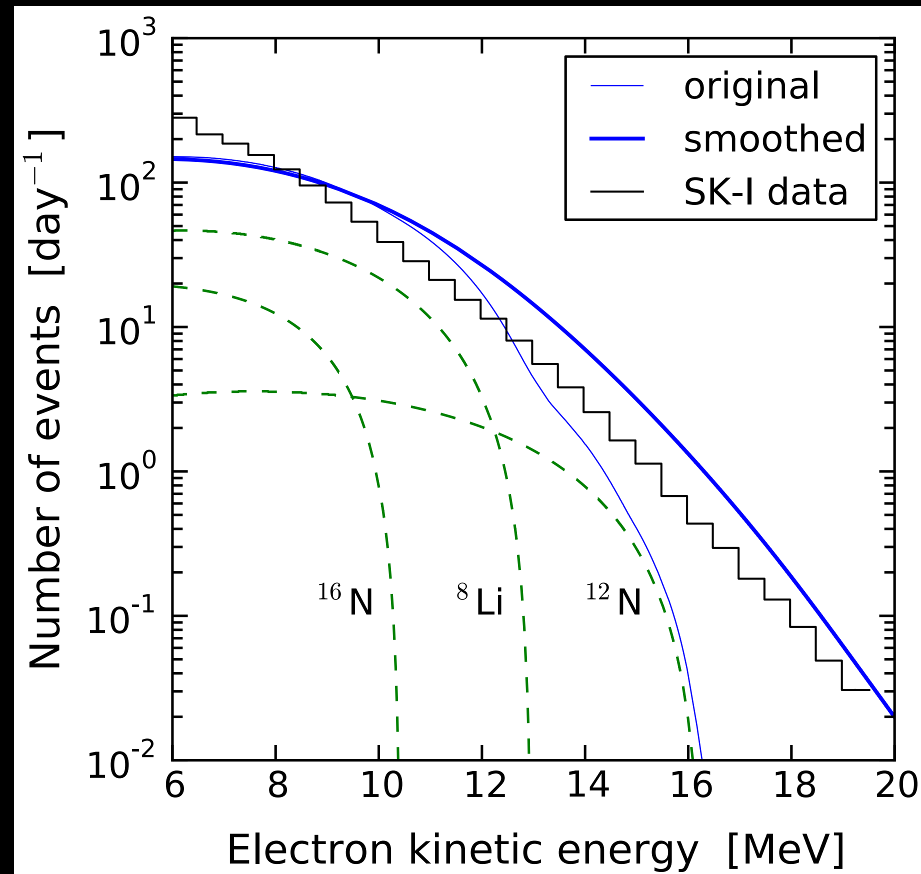
Isotope	Half-life (s)	Yield (E > 3.5 MeV) ($\times 10^{-7} \mu^{-1} g^{-1} cm^2$)	Primary process
n			
^{18}N	0.624	0.01	^{18}O(n,p)
^{17}N	4.173	0.02	^{18}O(n,n+p)
^{16}N	7.13	18	(n,p)
^{16}C	0.747	0.003	(π^-,n+p)
^{15}C	2.449	0.28	(n,2p)
^{14}B	0.0138	0.02	(n,3p)
^{13}O	0.0086	0.24	(μ^-,p+2n+μ^-+π^-)
^{13}B	0.0174	1.6	(π^-,2p+n)
^{12}N	0.0110	1.1	(π^+,2p+2n)
^{12}B	0.0202	9.8	(n,α+p)
^{12}Be	0.0236	0.08	(π^-,α+p+n)
^{11}Be	13.8	0.54	(n,α+2p)
^{11}Li	0.0085	0.01	(π^+,5p+π^++π^0)
^{9}C	0.127	0.69	(n,α+4n)
^{9}Li	0.178	1.5	(π^-,α+2p+n)
^{8}B	0.77	5.0	(π^+,α+2p+2n)
^{8}Li	0.838	11	(π^-,α+^{2}H+p+n)
^{8}He	0.119	0.16	(π^-,^{3}H+4p+n)



Spallation yields vary greatly, depend on MeV reactions

Spallation Decays and their Properties



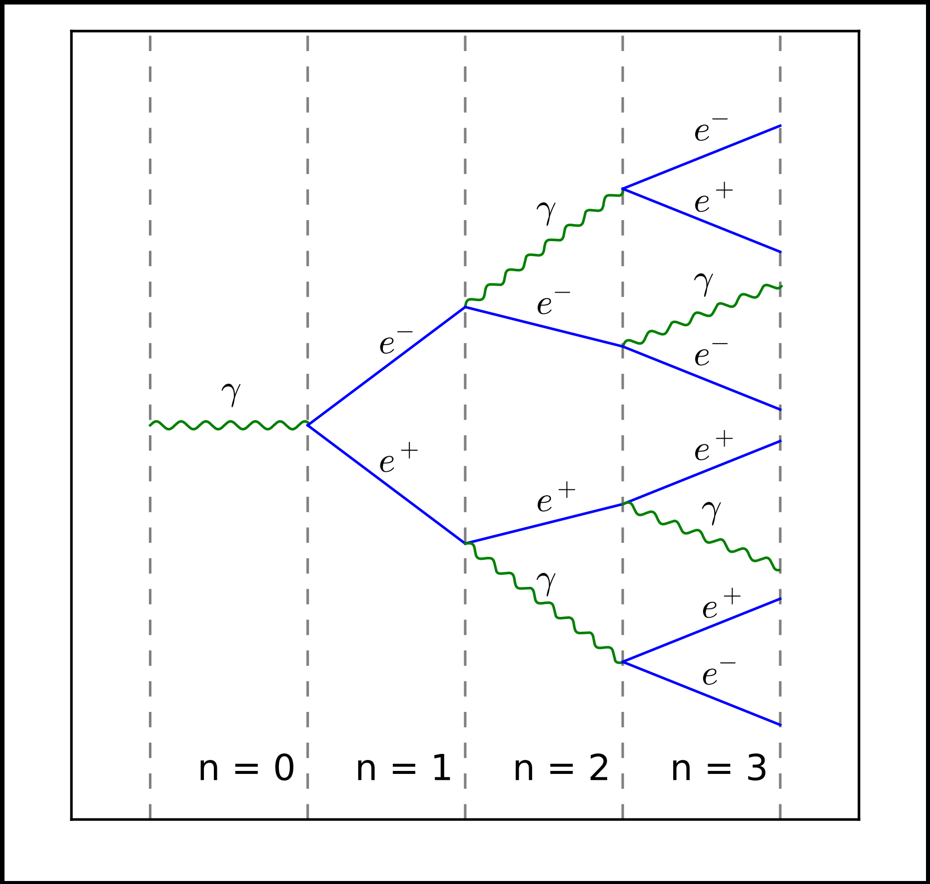


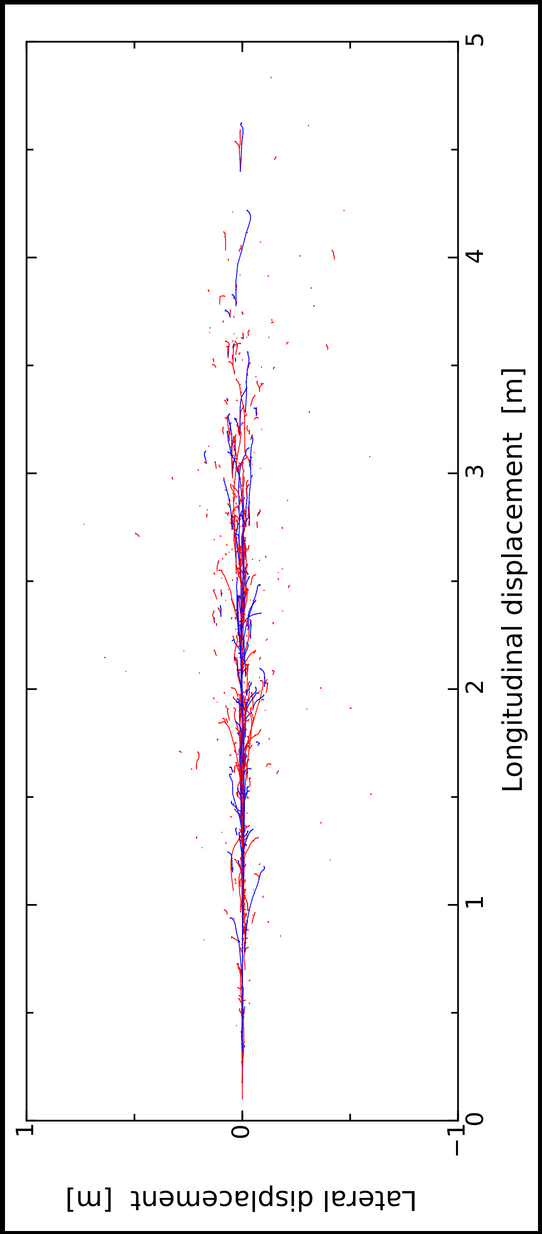
Time and energy distributions agree with Super-K data

Spallation: the summoning

Li and Beacom 2015a [arXiv:1503.04823]
Isotopes are made in showers and are calculable

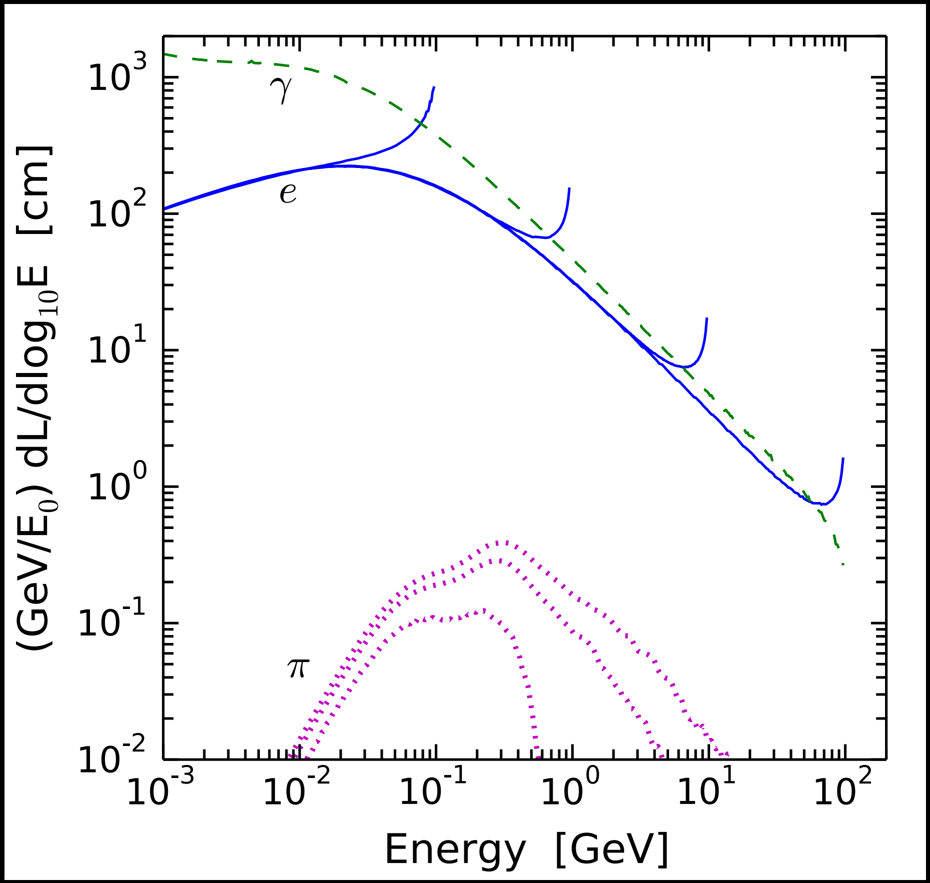
Showers in Concept and Practice

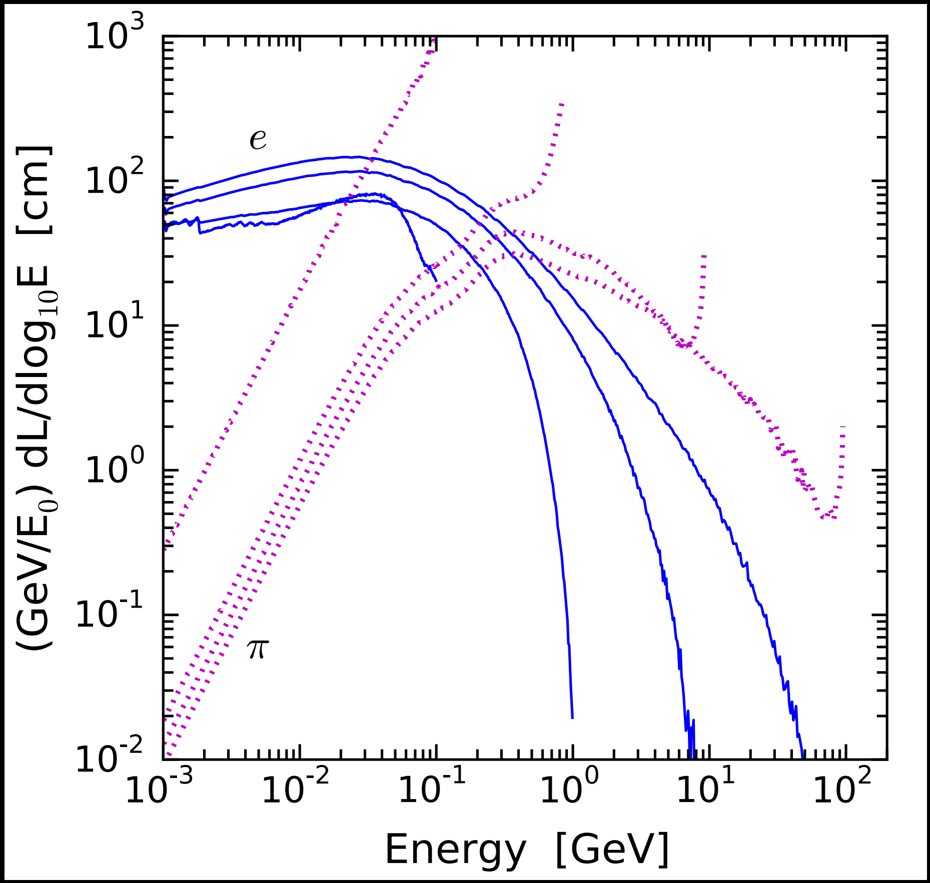




High-energy particles make showers

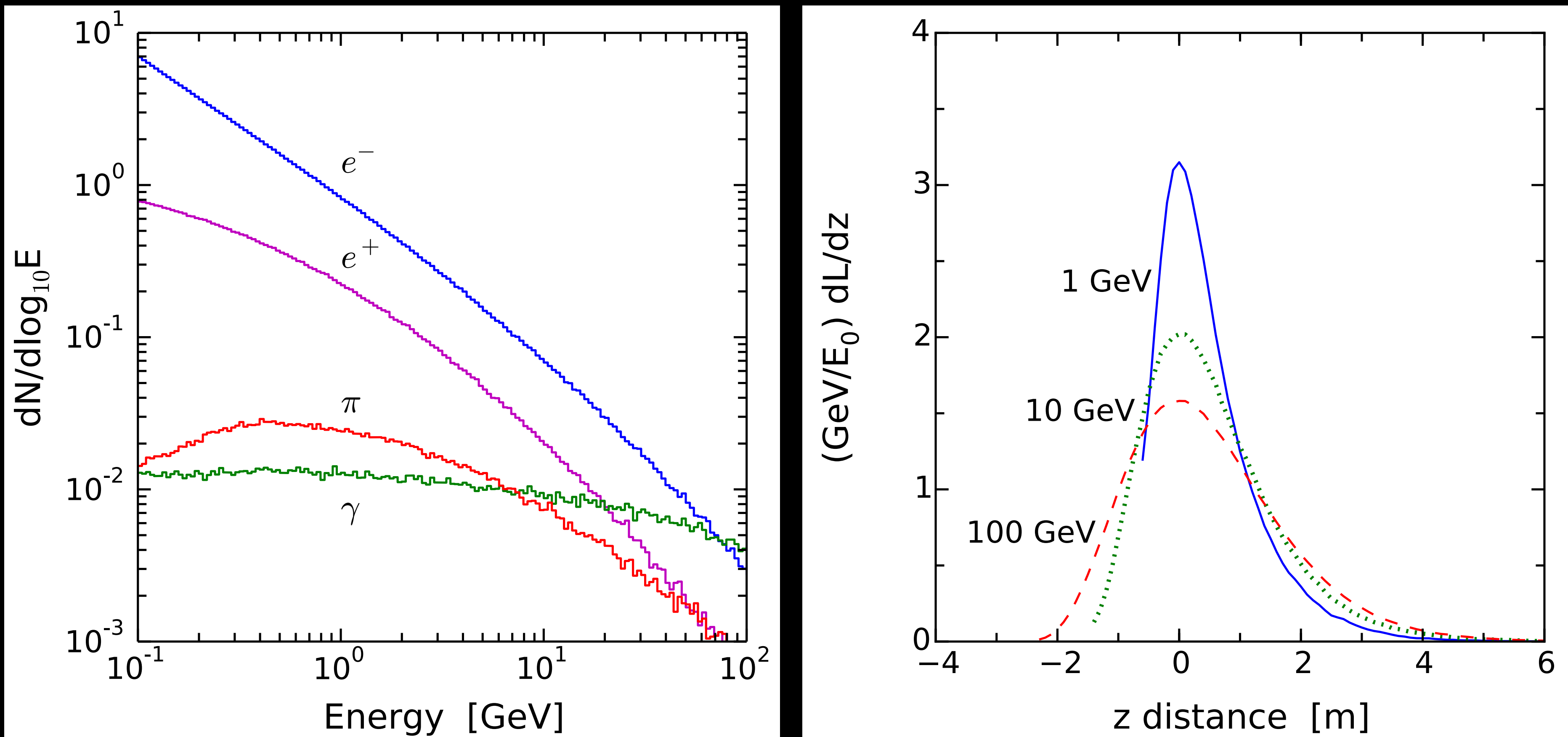
Secondary Path Length Spectra from Showers





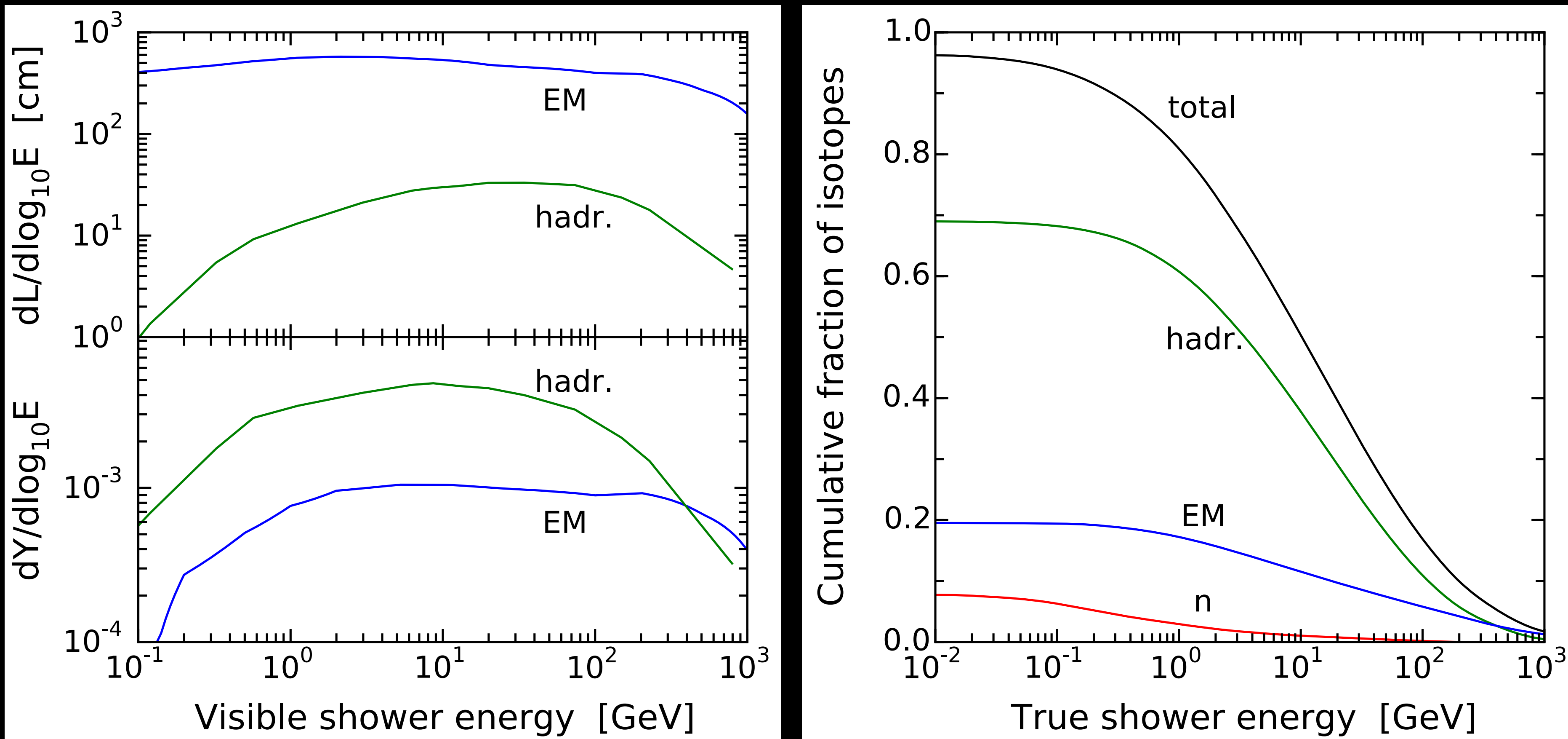
Path length spectra from showers are near universal

Muon-Induced Showers and their Properties



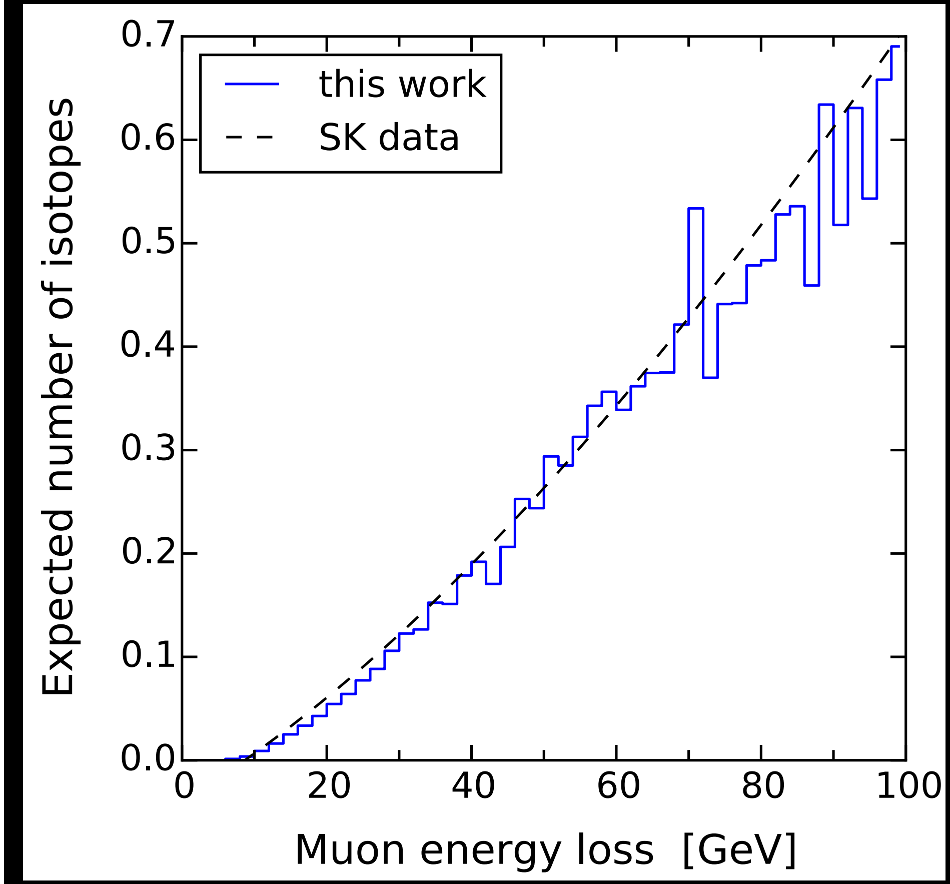
Muons make showers of different types, broad spectrum

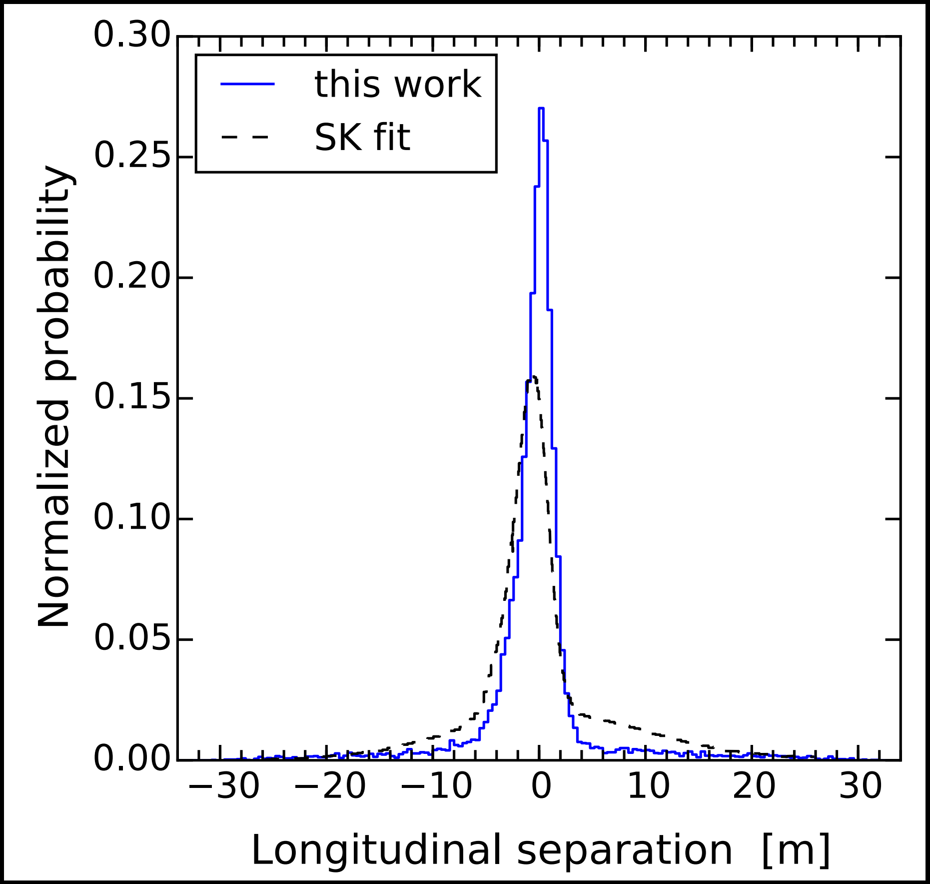
Light and Isotope Production by Showers



EM showers make light but not isotopes; hadronic is opposite

Correlations of Showers and Isotopes



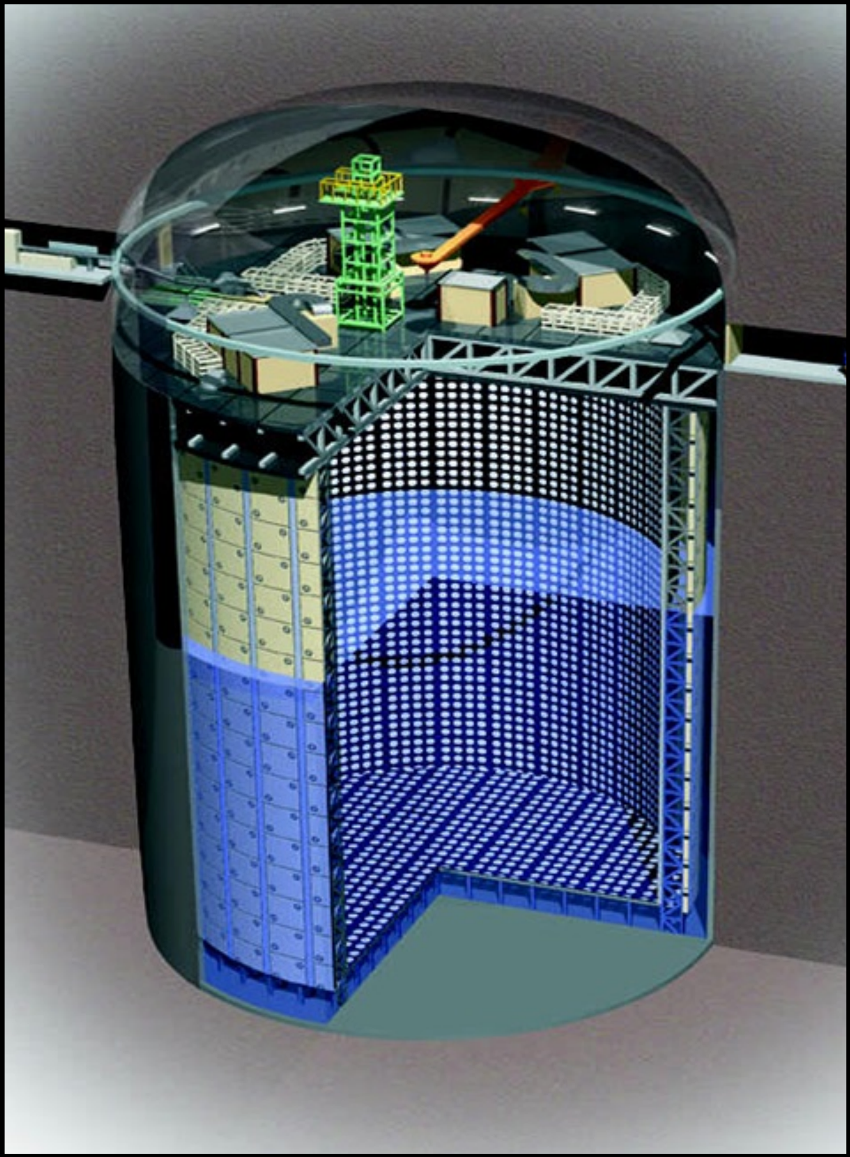


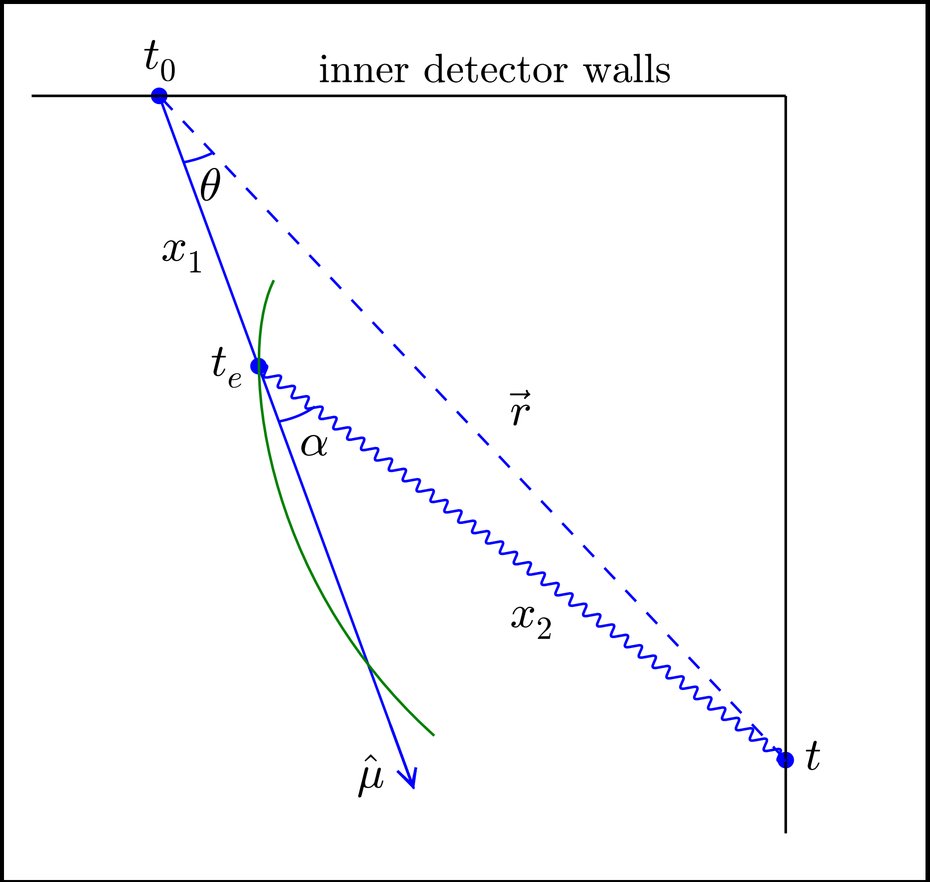
Isotope production follows muon energy loss

Spallation: the vengeance

Li and Beacom 2015b [arXiv:1508.05389]
Isotope production can be identified and localized

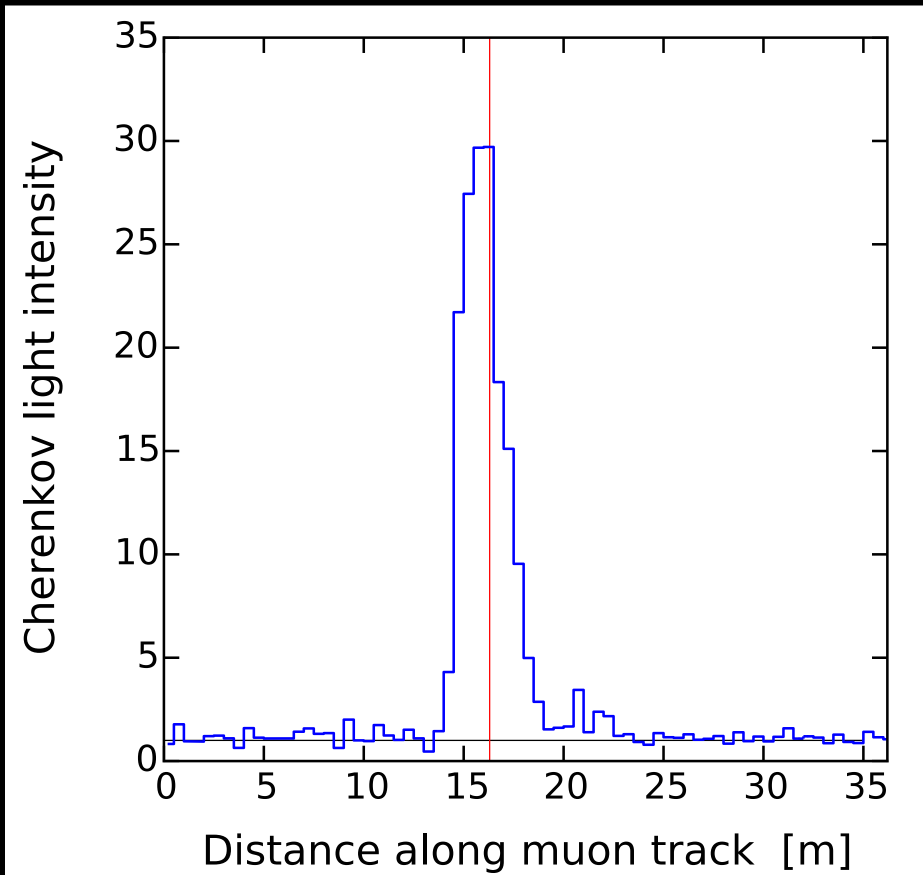
Showers Produce Lots of Light

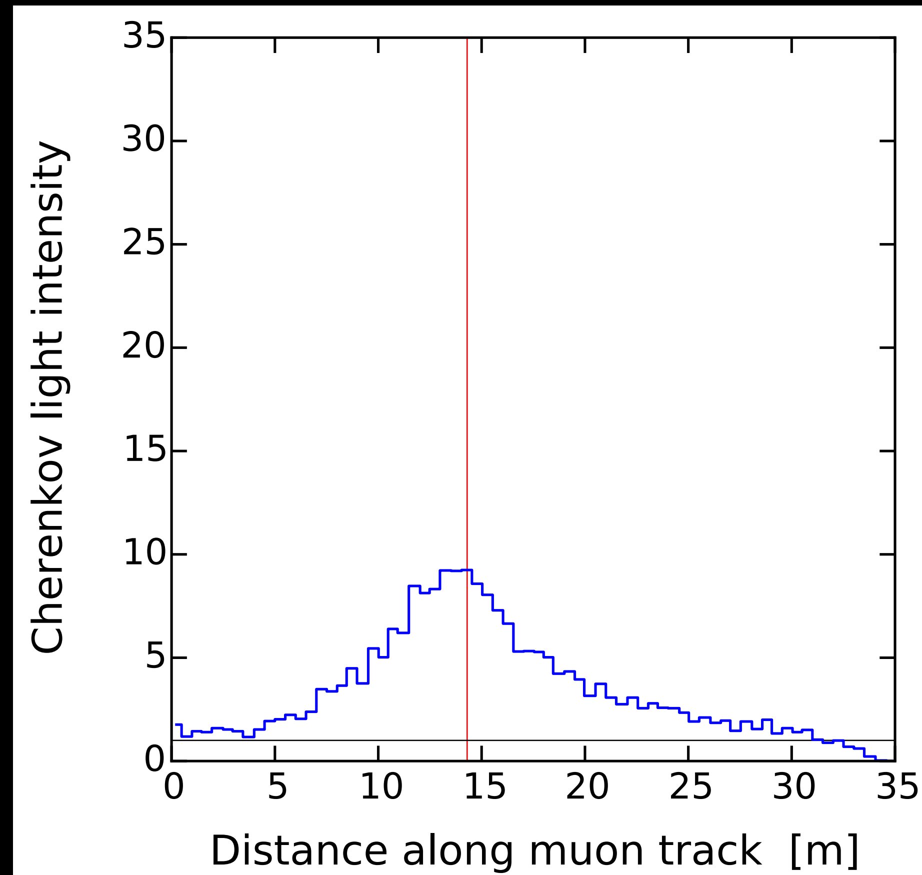




Can we reconstruct the shower?

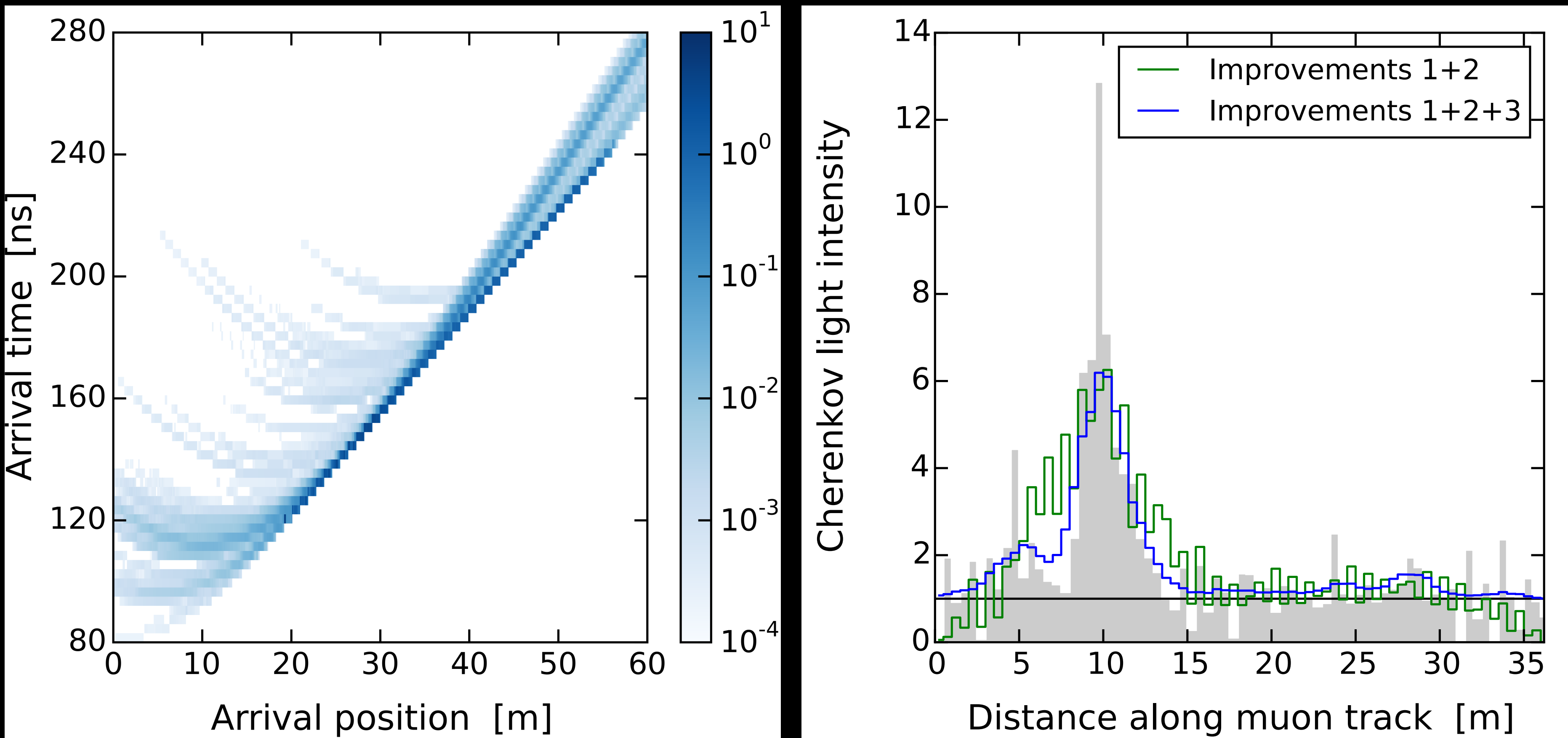
Where is the Shower?





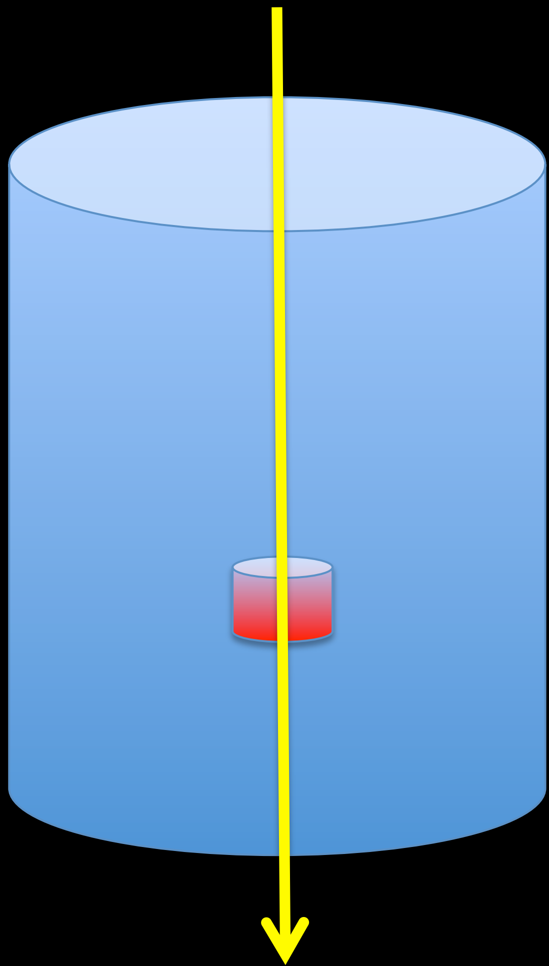
Left shows Monte Carlo truth; right shows Super-K reality

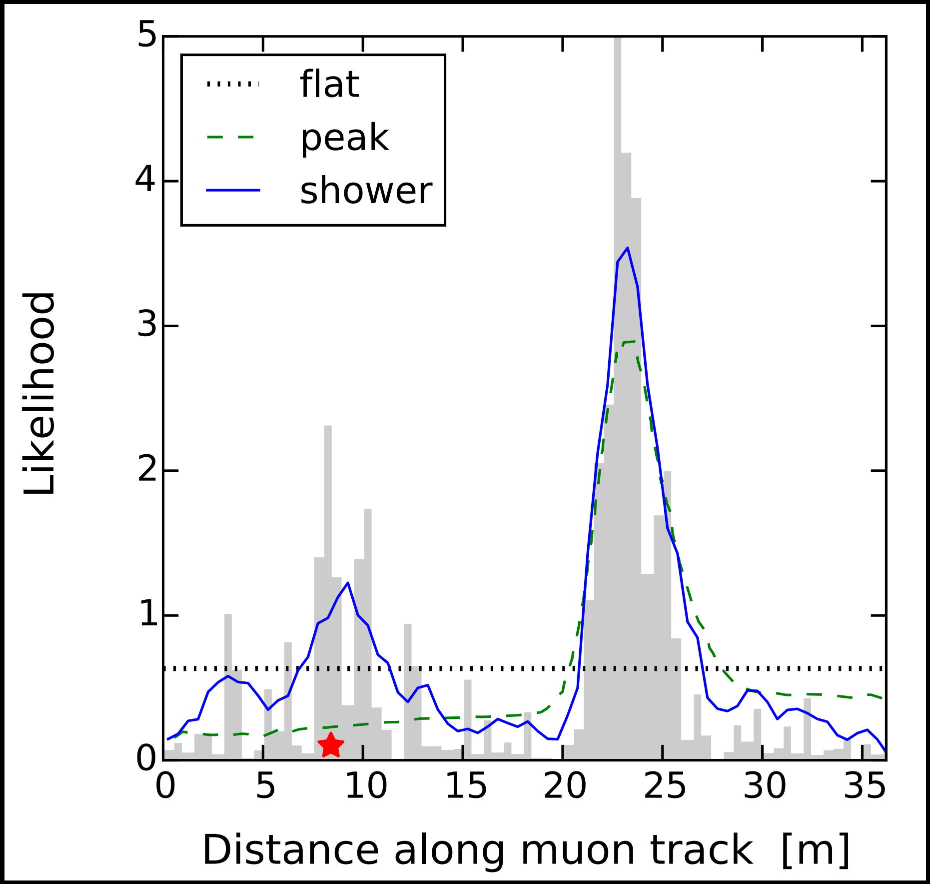
Reconstruction Using all PMT Hits



We can rebuild it

Bespoke Cuts for Every Muon





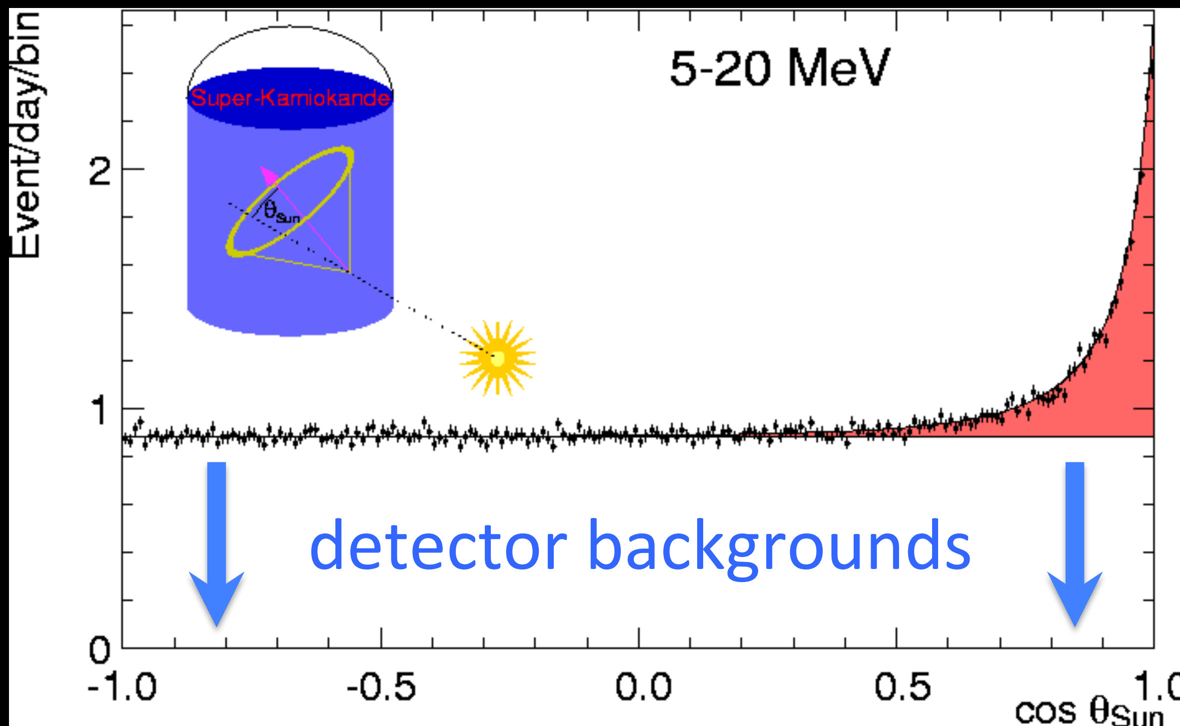
Harder cuts, smaller volume: better efficiency, less deadtime

Eliminating Spallation Backgrounds

First cut:
Rare but dangerous high-energy showers

Second cut:
Restrict cuts to near shower positions

Third cut (in devel.):
Rare but dangerous hadronic showers

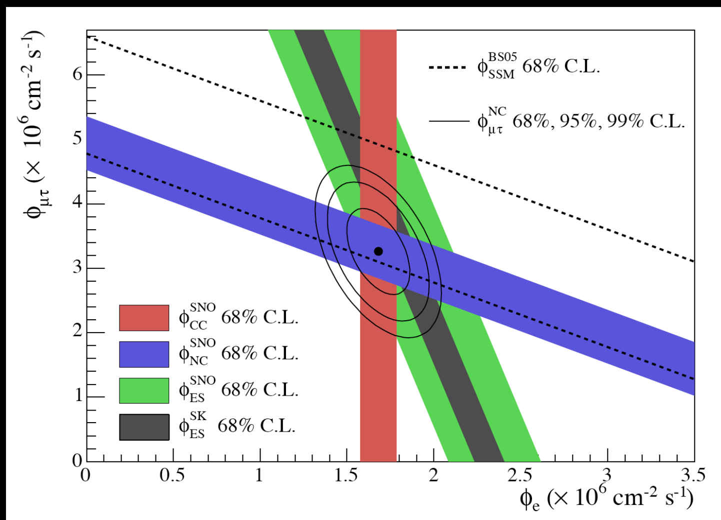


Super-K is already adopting our techniques; more to come
Expect to reduce backgrounds in all MeV detectors by ~ 10

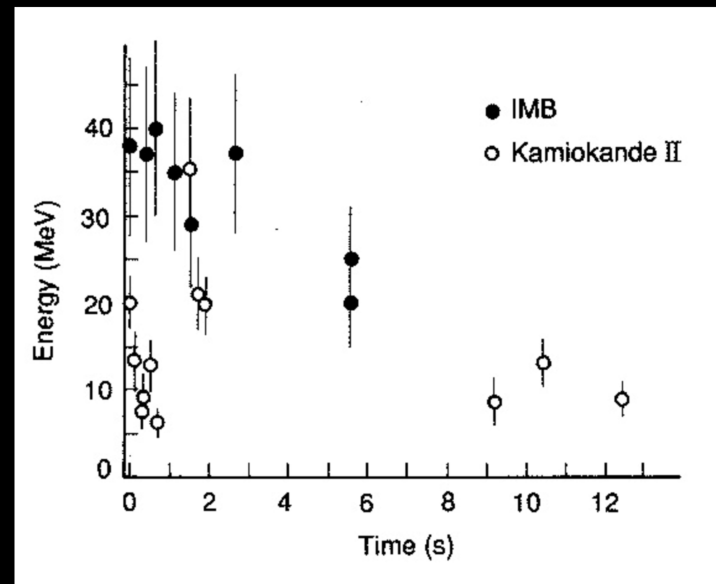
Back to the future with neutrino physics

MeV Neutrinos – What are They Good For?

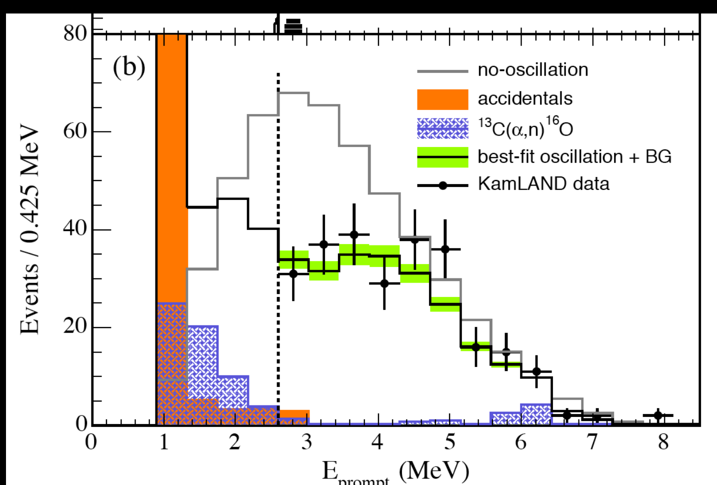
Solar



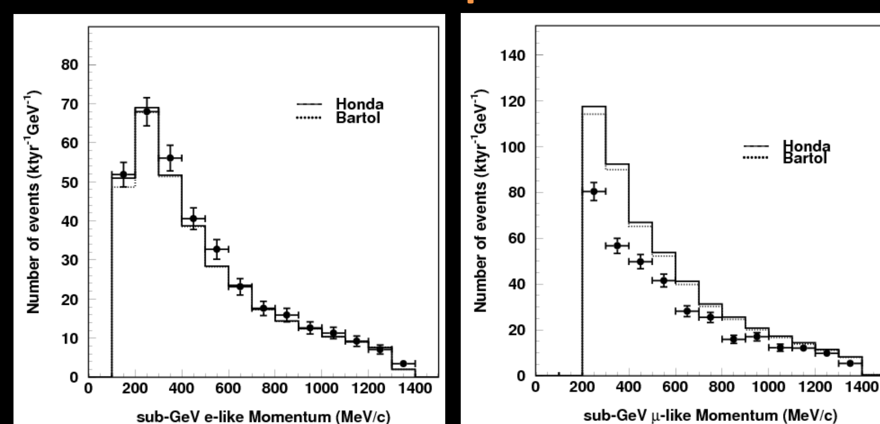
Supernova



Reactor

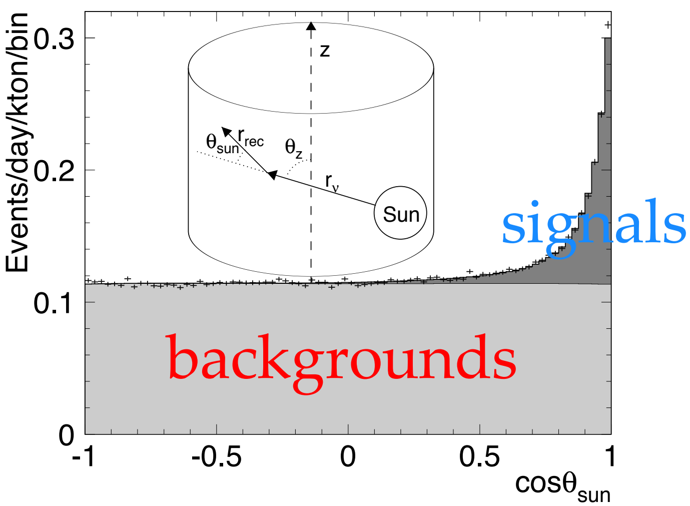


Atmospheric

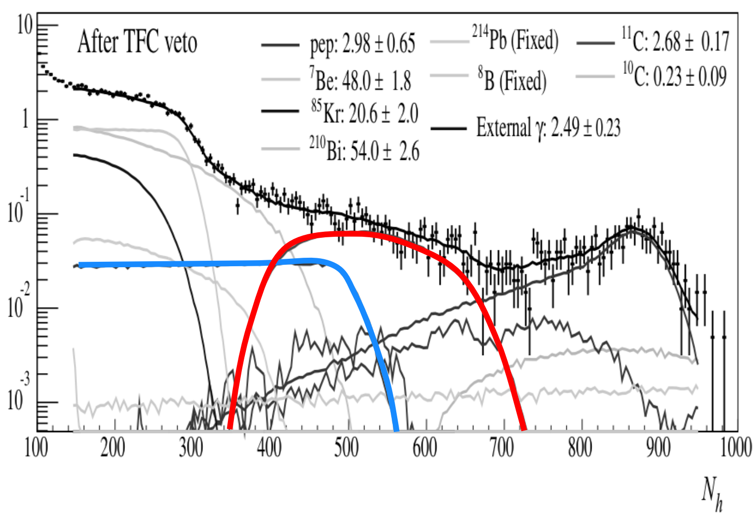


Examples of Spallation Backgrounds

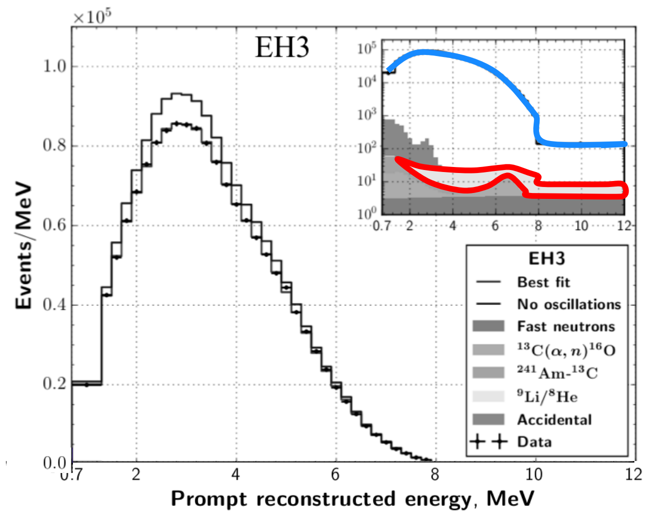
^{8}B solar neutrino



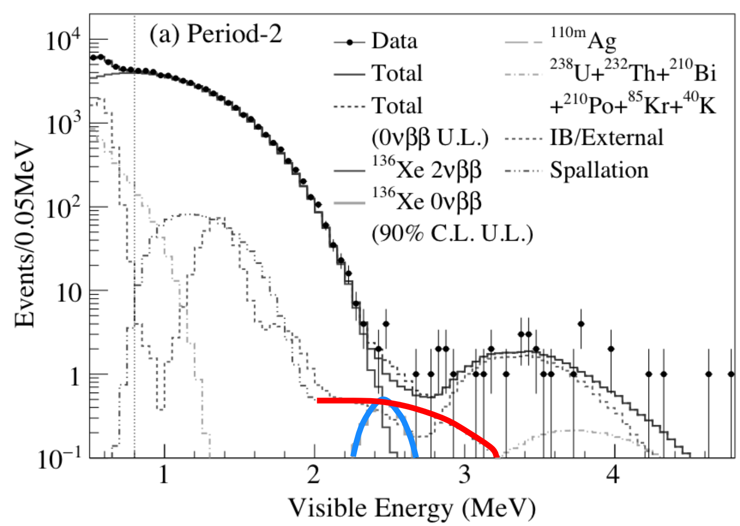
pep, CNO solar neutrino



reactor neutrino



0νββ



Take-Away Messages

Important physics depends on detecting MeV neutrinos

With better detectors, signal ID, and backgrounds, we can

Understanding spallation backgrounds is a new opportunity
Theoretical insights are crucial to progress
Backgrounds are made by secondaries
Secondaries are made in showers
Showers can be identified and localized
Applicability to a wide range of underground detectors

Shirley Li is applying for postdocs this fall:
Works on neutrino physics and detection, also neutron stars

Center for Cosmology and AstroParticle Physics

CCAPP

The Ohio State University's Center for Cosmology and AstroParticle Physics

Columbus, Ohio: 1 million people (city), 2 million people (city+metro)
Ohio State University: 56,000 students
Physics: 55 faculty, Astronomy: 20 faculty
CCAPP: 20 faculty, 10 postdocs from both departments
Placements: *In 2014 alone, 12 CCAPP alumni got permanent-track jobs*

ccapp.osu.edu

Recent faculty hires: Antonio Boveia, Linda Carpenter, Chris Hirata, Adam Leroy, Laura Lopez, Annika Peter
Recent PD hires: Ami Choi, Alexia Lewis, Niall MacCran, Tuguldur Sukhbold, Michael Troxel, Ying Zu, … and Francesco Capozzi

CCAPP Postdoctoral Fellowship applications welcomed this Fall